Hot Quarks 2016, South Padre Island

Steffen Weber for the ALICE collaboration

September 14, 2016

Measurements of J/ψ production in pp collisions at LHC energies with ALICE

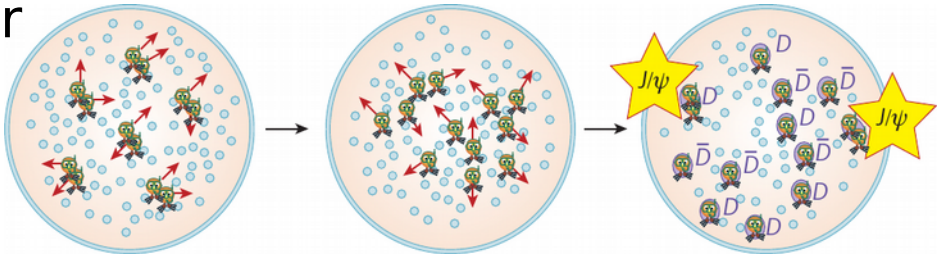
Outline

- Physics motivation
- Analysis methods at central and forward rapidity
- Highlights from LHC Run-1
  - J/ψ transverse momentum spectrum
  - J/ψ production versus charged-particle multiplicity
- First look at LHC Run-2 pp data at forward rapidity
- Summary and outlook

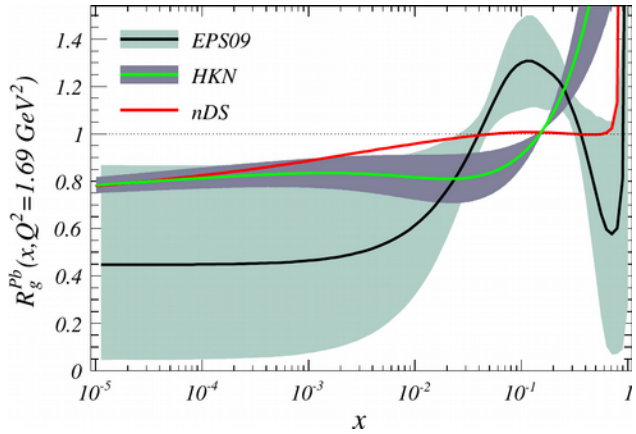
Motivation 1: J/ψ in pp collisions as reference

Charmonium production in pp collisions is a crucial baseline for

- Hot QCD matter effects in nucleus-nucleus collisions:
  - Color-screening
  - (Re)generation
- Additional cold nuclear matter effects already present in proton-nucleus collisions
  - Gluon saturation
  - (Anti-) shadowing
  - Partonic energy loss



P. Braun-Munzinger, J. Stachel: Nature, 448:302–309 (2007)



C. A. Salgado et al.: J.Phys. G39 (2012) 015010

Motivation 2: J/ψ in pp collisions to understand QCD

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Charmonium production is an intrinsically multiscale process:

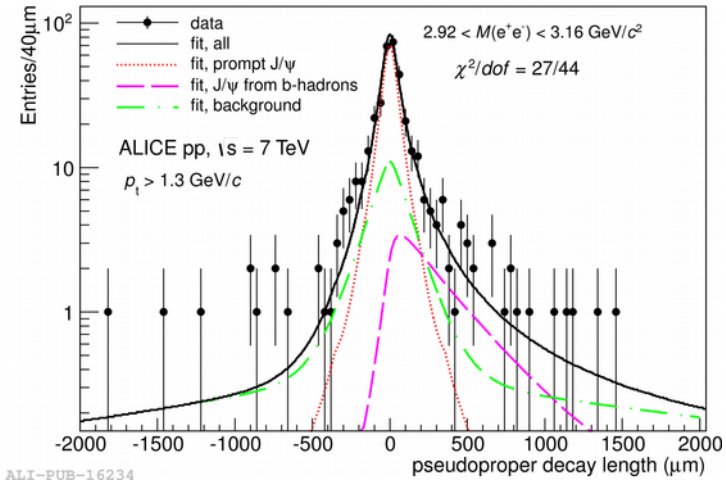
- Heavy-quark pair production: hard scale → regime of pQCD
- Binding into charmonium: soft scale

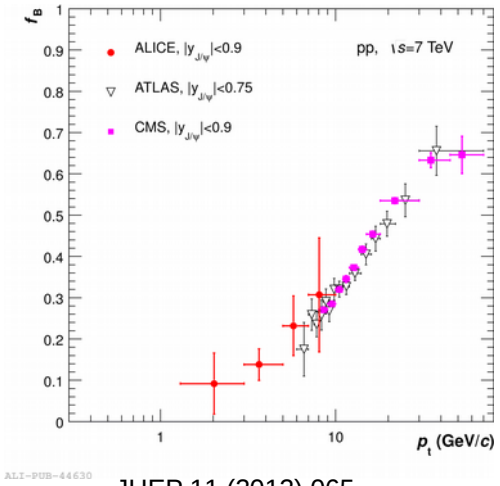
Different models try to describe the complex process:

- **C**olor **E**vaporation **M**odel: Based on quark-hadron duality. Cross section of given quarkonium state proportional to cross section of constituting heavy quark pair, independent of energy, transverse momentum or rapidity.
- **C**olor **S**inglet **M**odel: $c\bar{c}$ produced on-shell with same quantum numbers as charmonium state → only **C**olor **S**inglet states.
- **N**on-**R**elativistic **QCD**: Also **C**olor **O**ctet states taken into account. Expansion in powers of the relative velocity of the heavy quarks, fitted in terms of long-range matrix elements.

None of the models provide full description of all aspects of charmonium production, e.g. polarization, p_T and energy dependence.

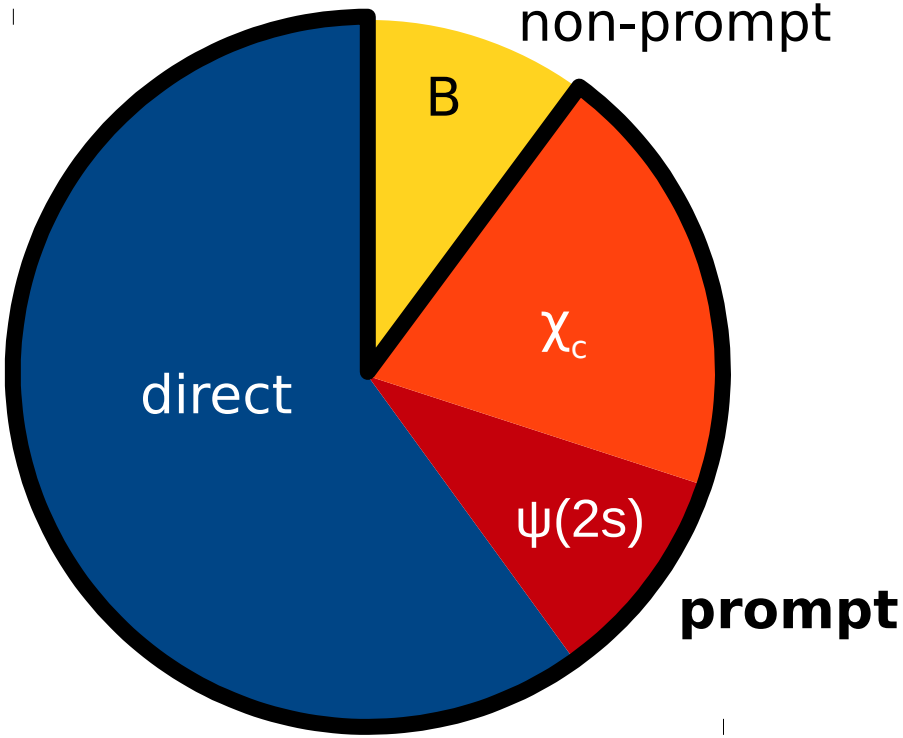
Sources of J/ψ production





JHEP 11 (2012) 065

Inclusive J/ψ production:



At mid-rapidity, fraction of non-prompt contribution can be quantified with simultaneous fit of the invariant mass and pseudoproper decay length

The ALICE detector

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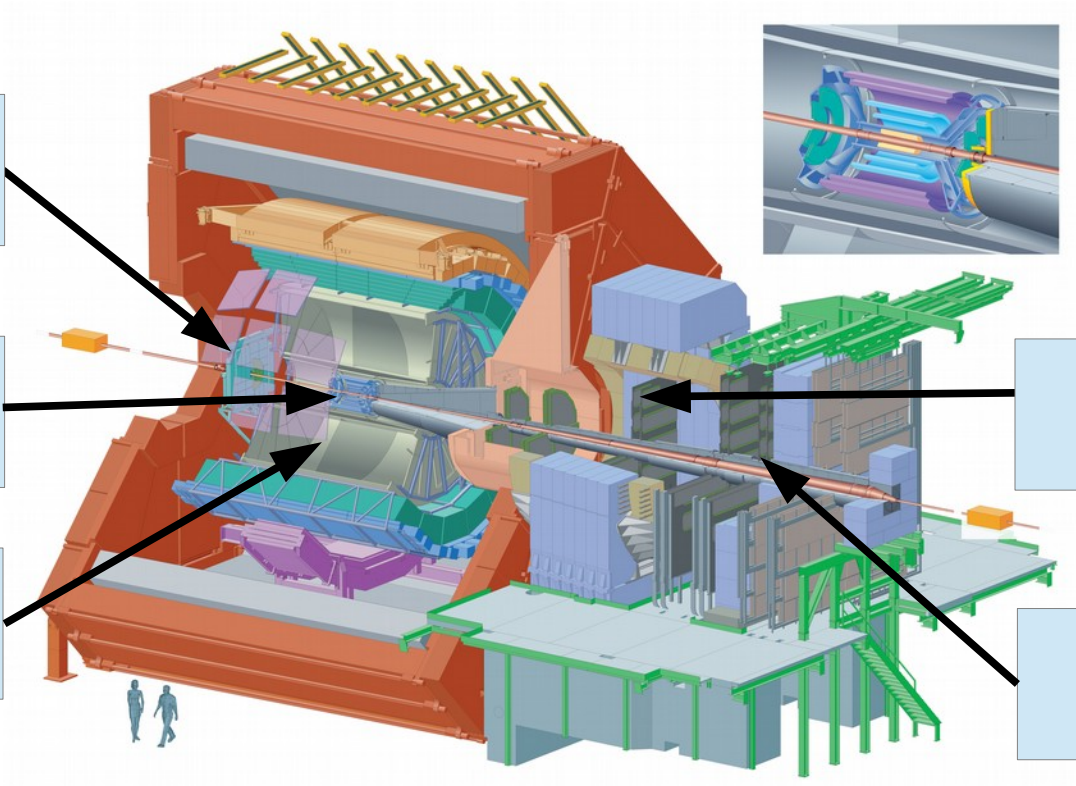
$J/\psi \rightarrow e^+e^-$: central barrel
$|\eta| < 0.9$

$J/\psi \rightarrow \mu^+\mu^-$: muon arm
$-4.0 < \eta < -2.5$



V0
event selection

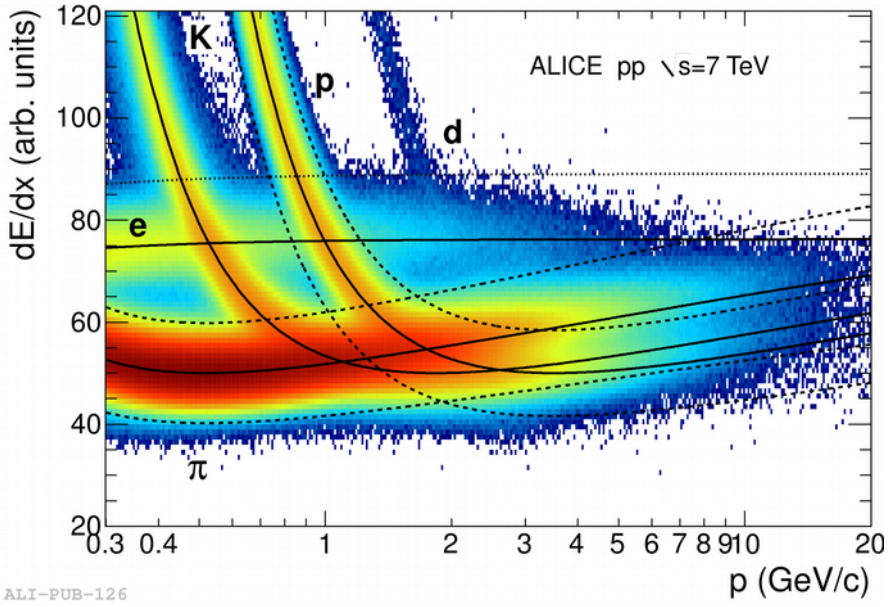
ITS
vertexing, tracking

TPC
tracking, PID

MCH
tracking

MTR
PID, trigger

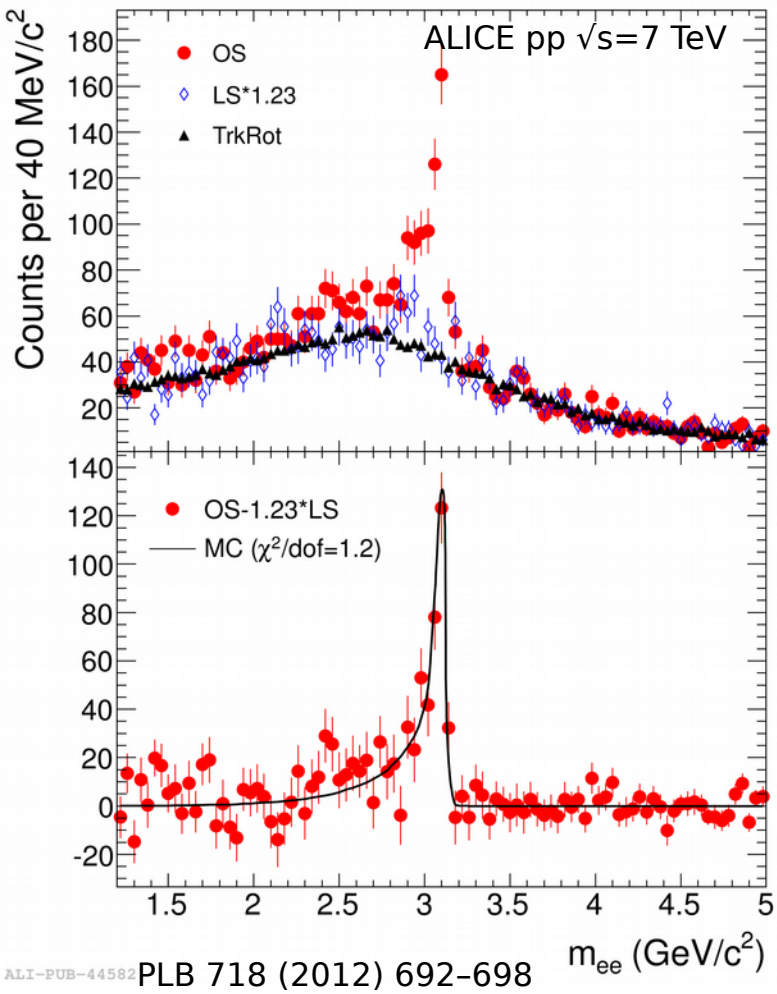
Analysis at mid-rapidity



PLB 704 (2011) 442–455

- Minimum bias event selection based on a signal in V0
- Track selection based on quality cuts
- PID based on TPC d*E*/d*x*: signal within 3 σ from expected electron line, exclusion of pion and proton lines
- Veto on tracks compatible with photon conversion

Analysis at mid-rapidity

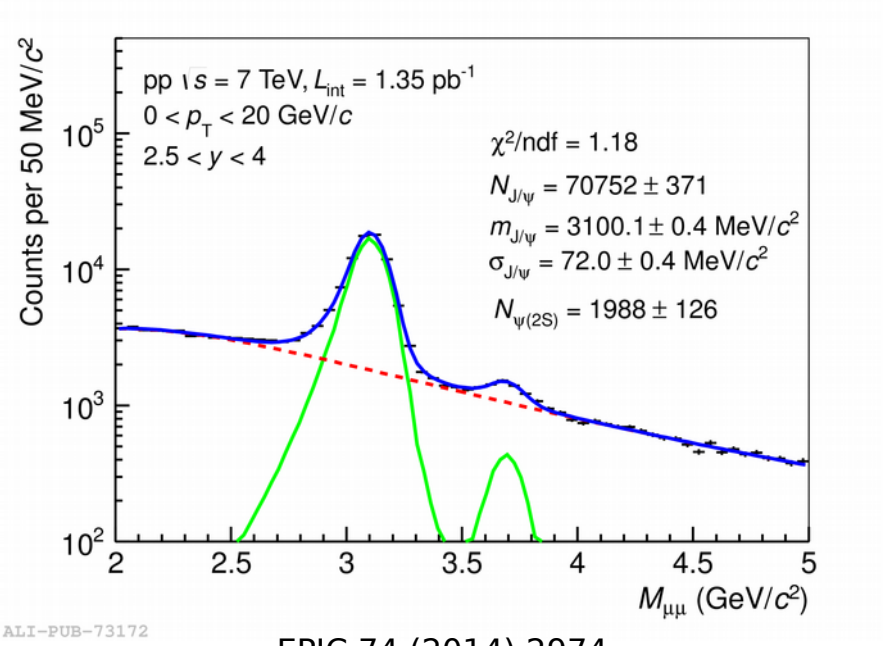


PLB 718 (2012) 692–698

- Invariant mass of opposite-sign electron pairs
- Background description with
  - like-sign pairs
  - track rotation
  - event mixing
- Signal extraction by bin counting in the invariant mass region of the expected signal after background subtraction

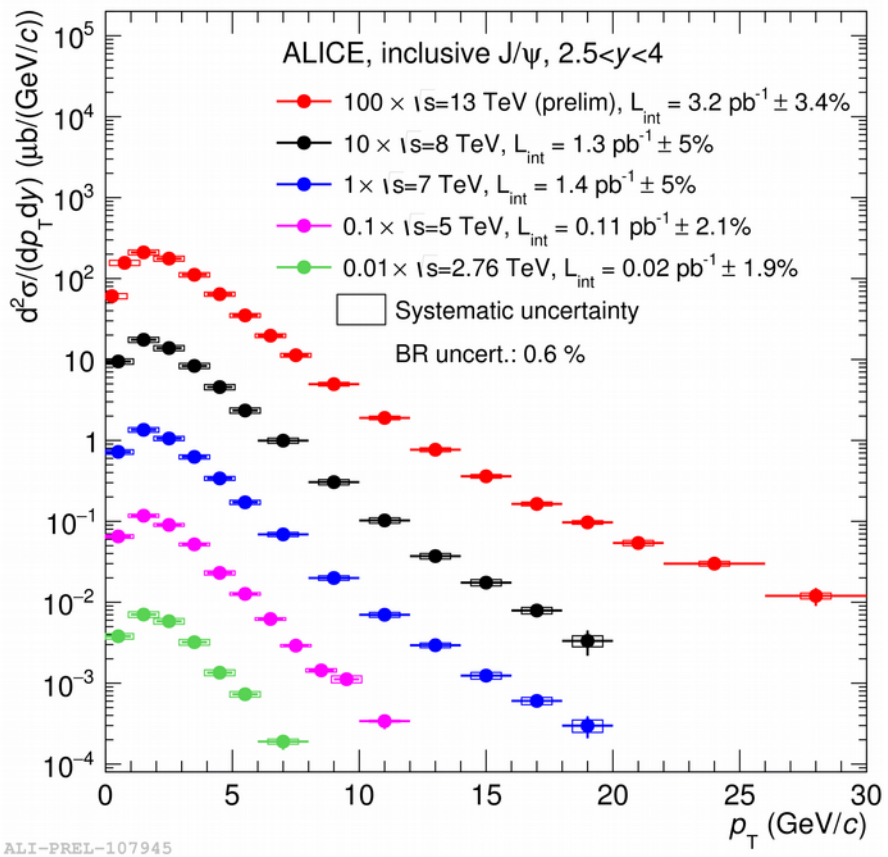
Analysis at forward rapidity

- Trigger on events with an opposite-sign muon pair
- Track quality cuts to reduce hadrons escaping from the front absorber, low p_T muons from decays, secondary and fake muons
- Yields extracted by fitting Crystal Ball functions to the J/ψ and ψ(2S) signals and Variable Width Gaussian to the background



EPJC 74 (2014) 2974

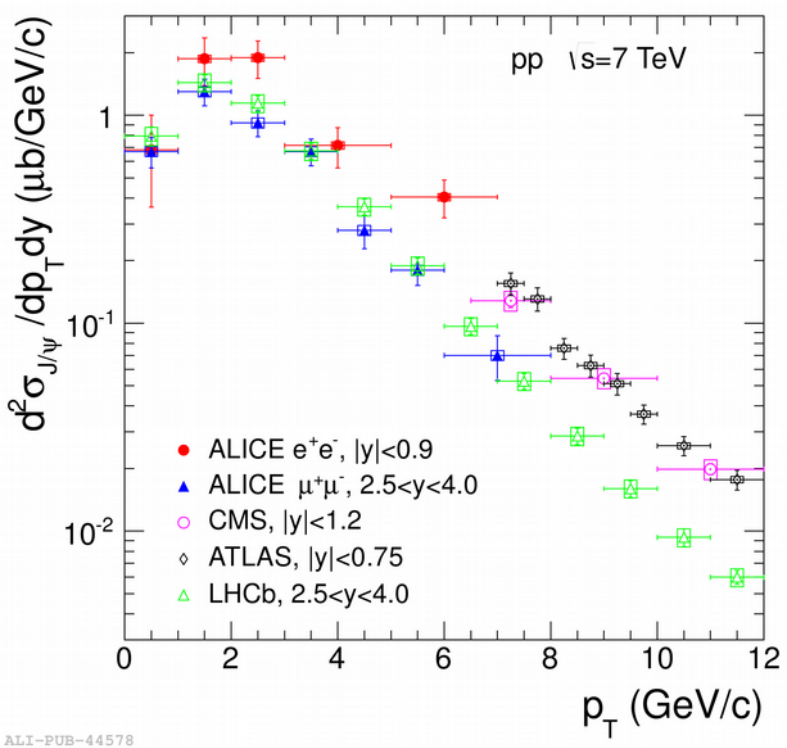
Overview of analyzed data sets

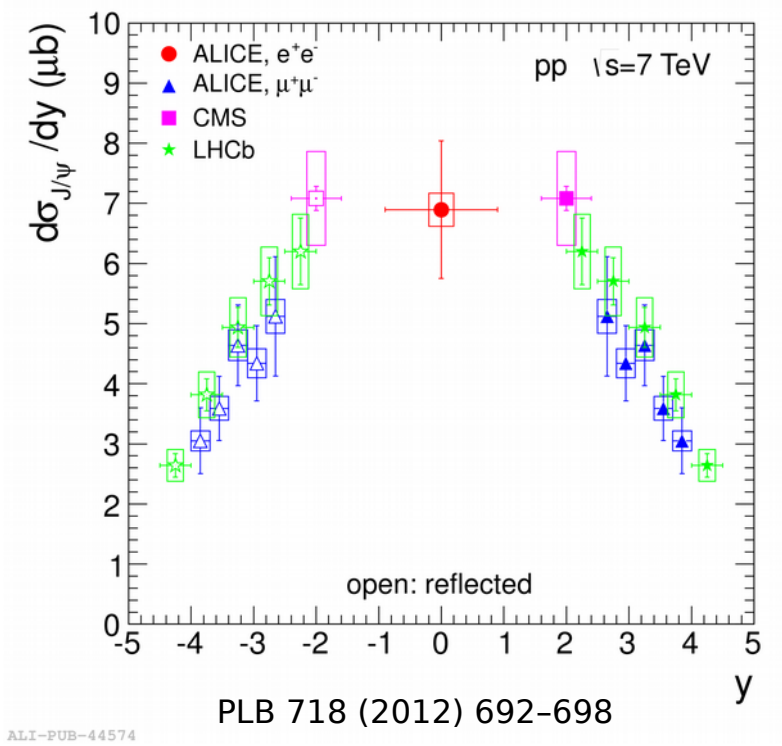


√s=2.76 TeV: PLB 718 (2012) 295
√s=5 TeV: arXiv:1606.08197
√s=7 TeV: EPJC 74 (2014) 2974
√s=8 TeV: EPJC 76 (2016) 184

- Rich set of analyzed data with collision energies from 2.76 TeV to 13 TeV
- Steady increase of luminosity and p_T reach with collision energy
- Hardening of spectra with energy
- Change of slope at high p_T: onset of non-prompt J/ψ contribution

p_T-differential and integrated cross section @ 7 TeV

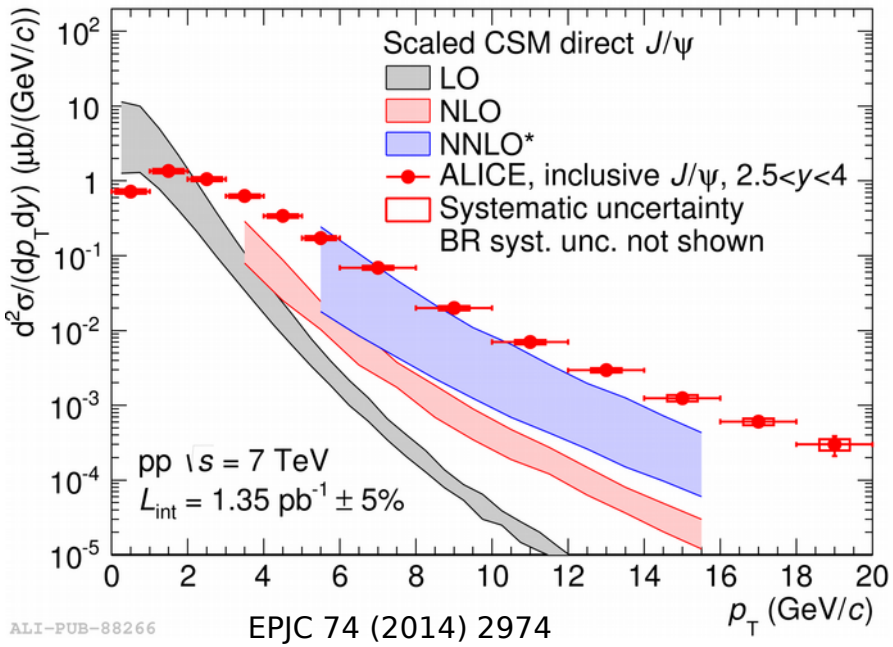




PLB 718 (2012) 692–698

- Forward rapidity: agreement between experiments
- Mid-rapidity: ALICE results are complementary to other LHC measurements at low p_T

Comparison to models: CSM

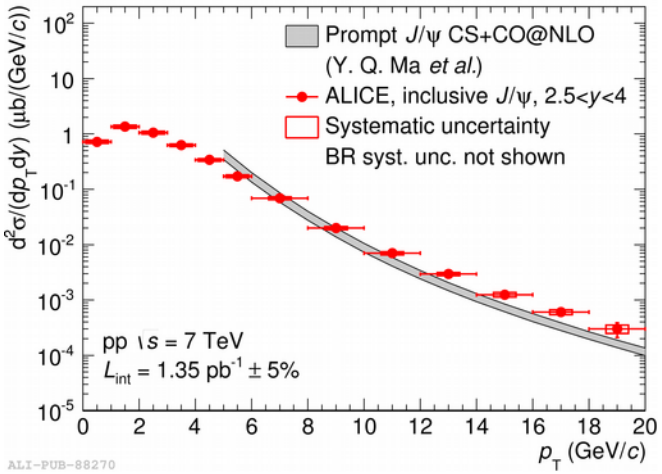


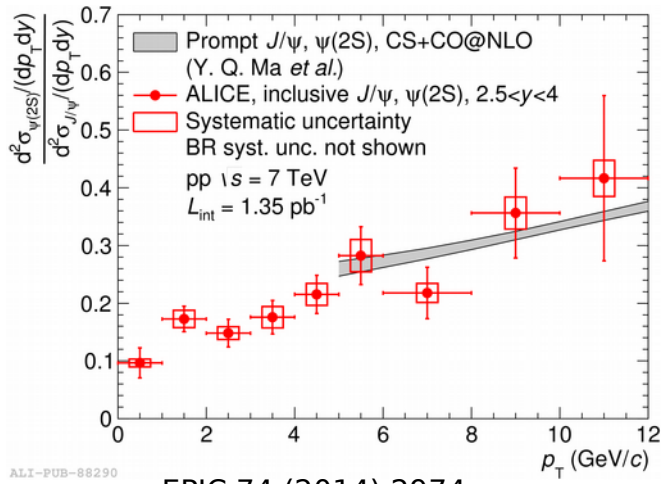
EPJC 74 (2014) 2974

Calculations: direct J/ψ production
Measurement: inclusive J/ψ
→ model scaled up with a constant

- LO and NLO underestimate the production, steeper p_T dependence
- Taking into account leading p_T NNLO contributions (NNLO*) moves model closer to data, p_T shape in better agreement, larger uncertainties

Comparison to models: NRQCD





EPJC 74 (2014) 2974

- Same NLO CS contributions as in CSM and CO contributions
- Models describe the data well
- Fixed-order perturbative description → cannot describe low p_T part
- Some uncertainties cancel when building the ratio ψ(2S) to J/ψ
- Observed increase in ψ(2S) to J/ψ ratio reproduced by models

J/ψ production vs. charged-particle multiplicity

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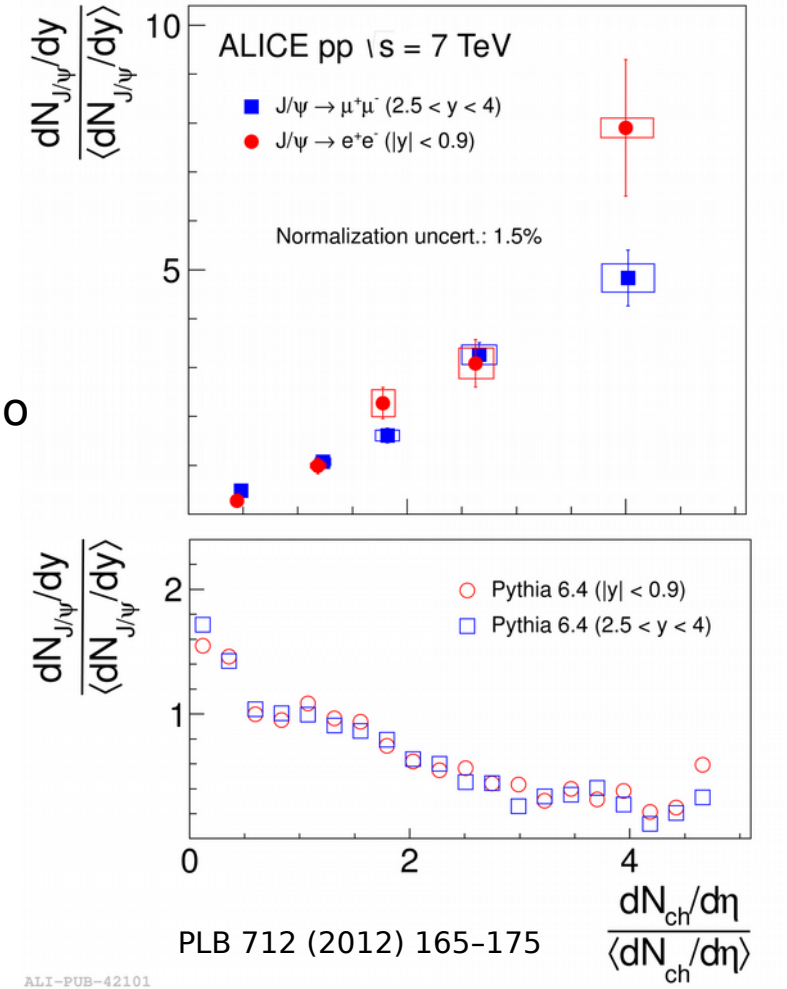
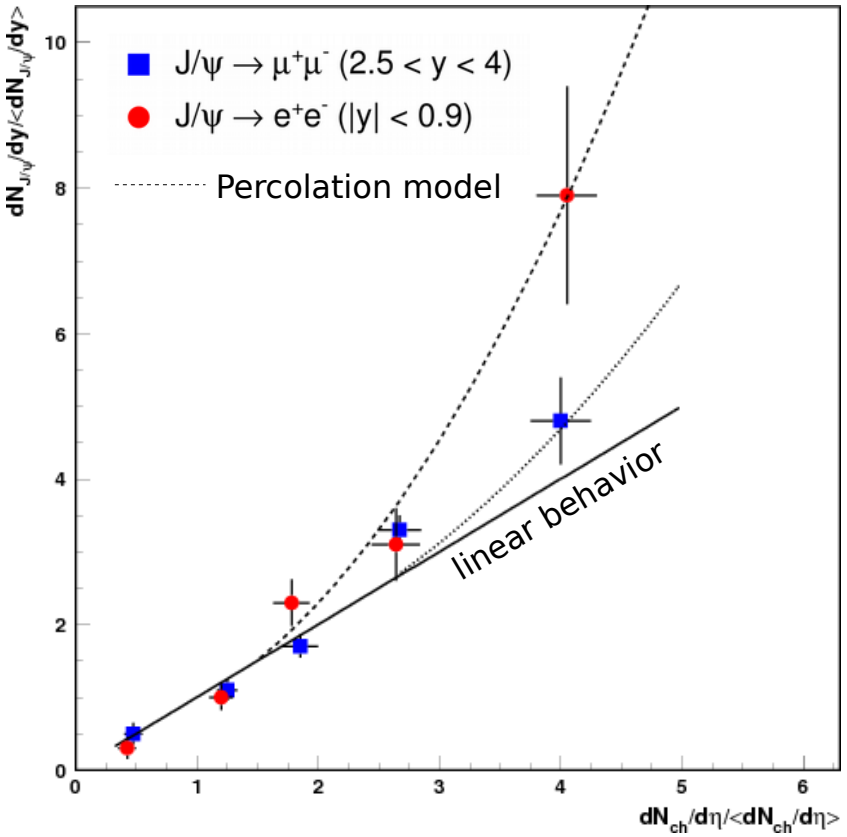
- Charged-particle multiplicity measured at mid-rapidity
- Approx. linear increase of J/ψ production with particle multiplicity both at mid- and forward rapidity
- Can not be understood by a simple 2→2 hard partonic scattering scenario



PLB 712 (2012) 165–175

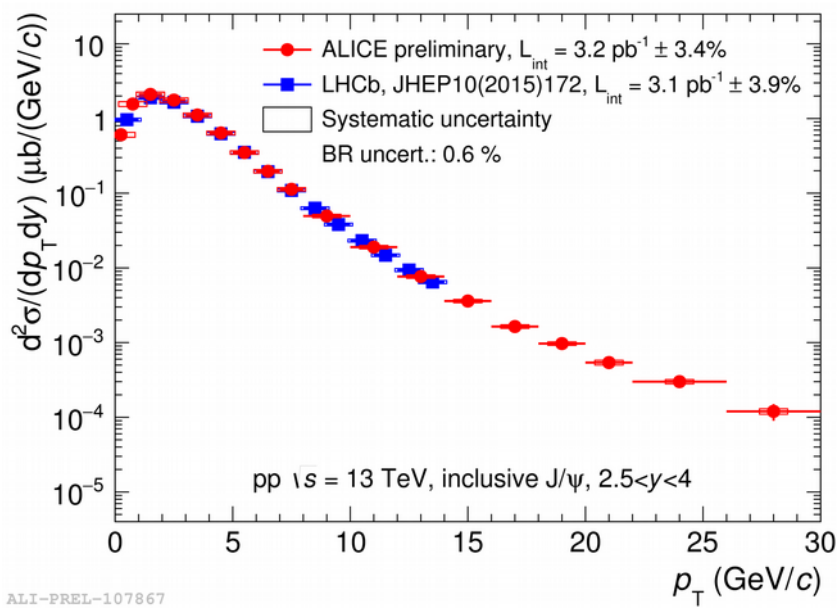
J/ψ production vs. charged-particle multiplicity

- Charged-particle multiplicity measured at mid-rapidity
- Approx. linear increase of J/ψ production with particle multiplicity both at mid- and forward rapidity
- Can not be understood by a simple 2→2 hard partonic scattering scenario
- Can be interpreted by the participation of heavy quarks in Multi-Parton Interactions
- Percolation model predicts stronger than linear increase for high multiplicities
- ALICE expects to extend this measurement to higher multiplicities



extracted from
PRC 86 (2016) 034903

p_T spectrum @ 13 TeV



- Excellent agreement between LHCb and ALICE

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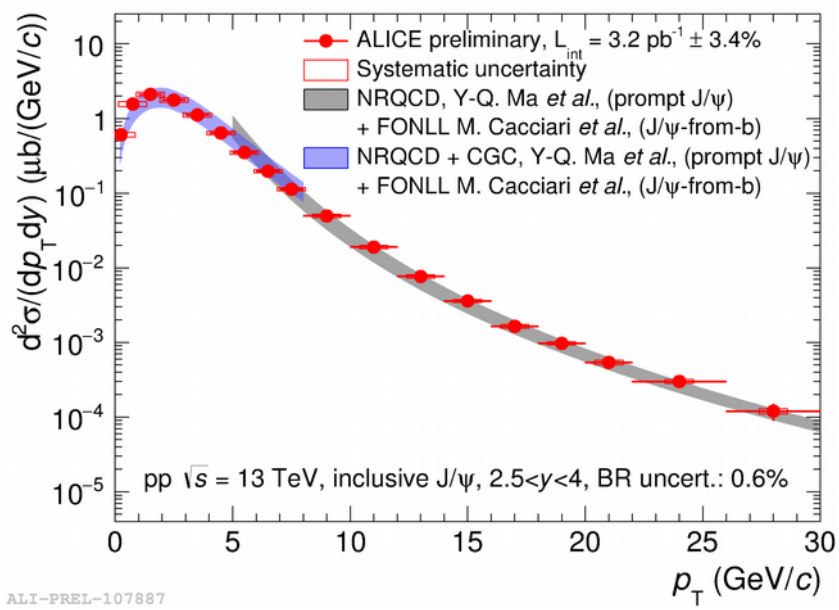
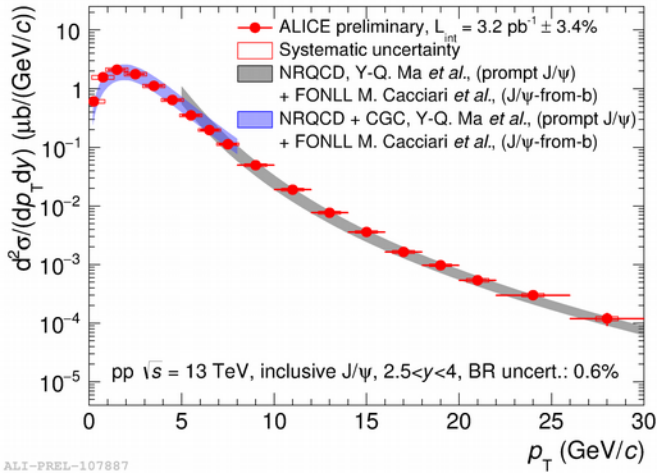
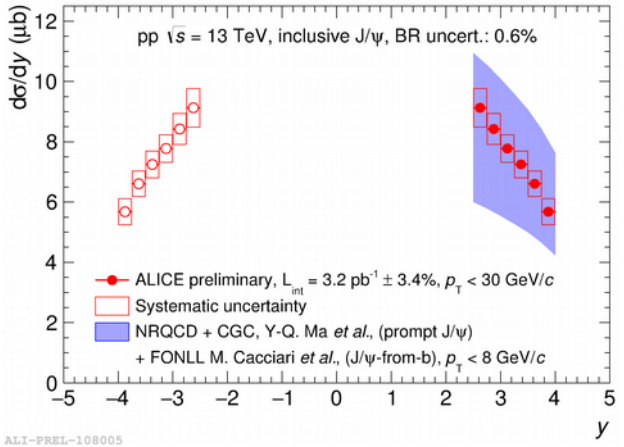


NRQCD: Ma, Wang and Chao, PRL 106 (2011) 042002
NRQCD+CGC: Ma and Venugopalan, PRL 113 (2014) 192301
FONLL: Cacciari et al., JHEP 1210 (2012) 13

- Excellent agreement between LHCb and ALICE
- Low p_T: NRQCD together with Color Glass Condensate description of the protons
- Proper handling of higher mass charmonium feed-down
- Description of B-meson feed-down from FONLL
- Sum of NRQCD prompt and FONLL non-prompt models agrees very well with data

p_T spectrum @ 13 TeV





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- Sum of NRQCD prompt and FONLL non-prompt models agrees very well with data
- Rapidity dependence of p_T-integrated cross-section in agreement with data

Summary

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- ALICE measures J/ψ production in pp collisions at various LHC energies down to zero p_T both at forward- and mid-rapidity
- The mid-rapidity measurement capabilities at low p_T are unique among the LHC experiments
- J/ψ production as a function of charged-particle multiplicity is a new observable that sheds light on the interplay between soft and hard QCD processes
- Results at $\sqrt{s}$= 13 TeV are in good agreement with LHCb and the NRQCD formalisms when taking properly into account the feed-down from higher charmonium states and B-mesons

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Thanks for your attention!

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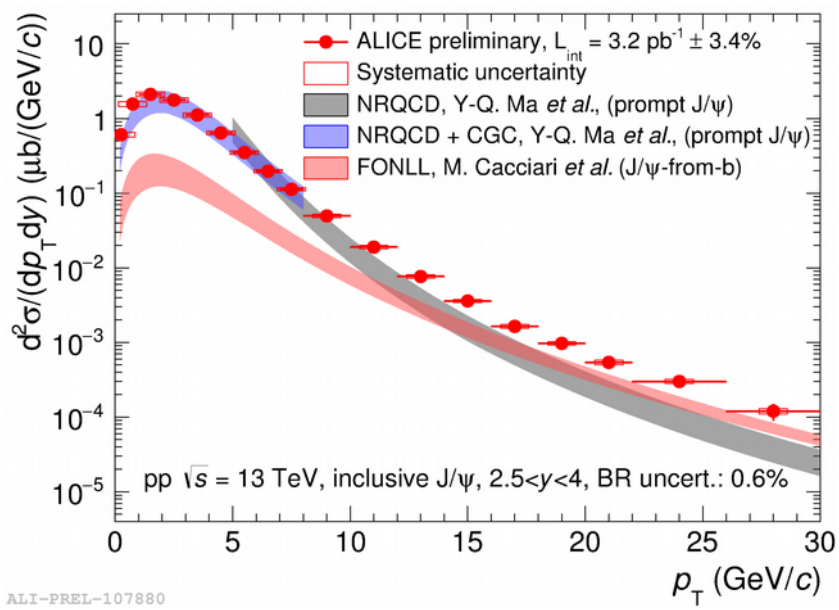
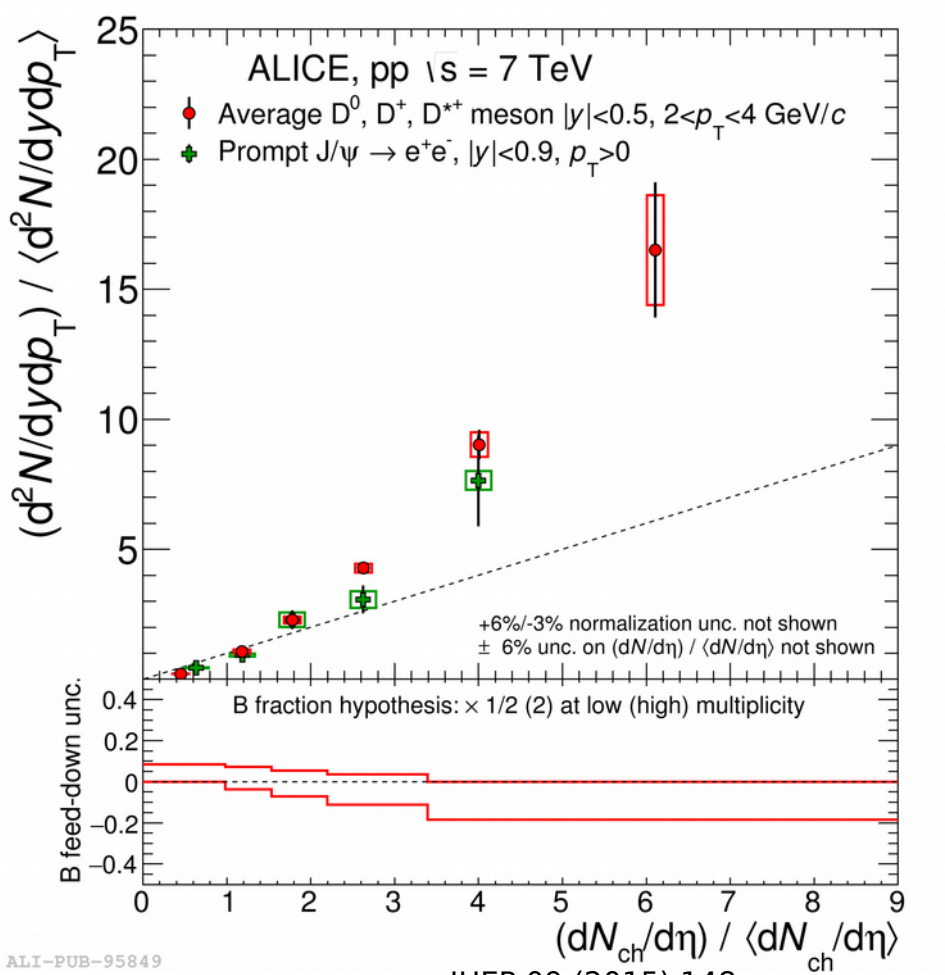
BACKUP

p_T spectrum @ 13 TeV



- Excellent agreement between LHCb and ALICE
- Low p_T: NRQCD together with Color Glass Condensate description of the protons
- Proper handling of higher mass charmonium feed-down
- Description of b-meson feed-down from FONLL

Heavy quark production as function of multiplicity

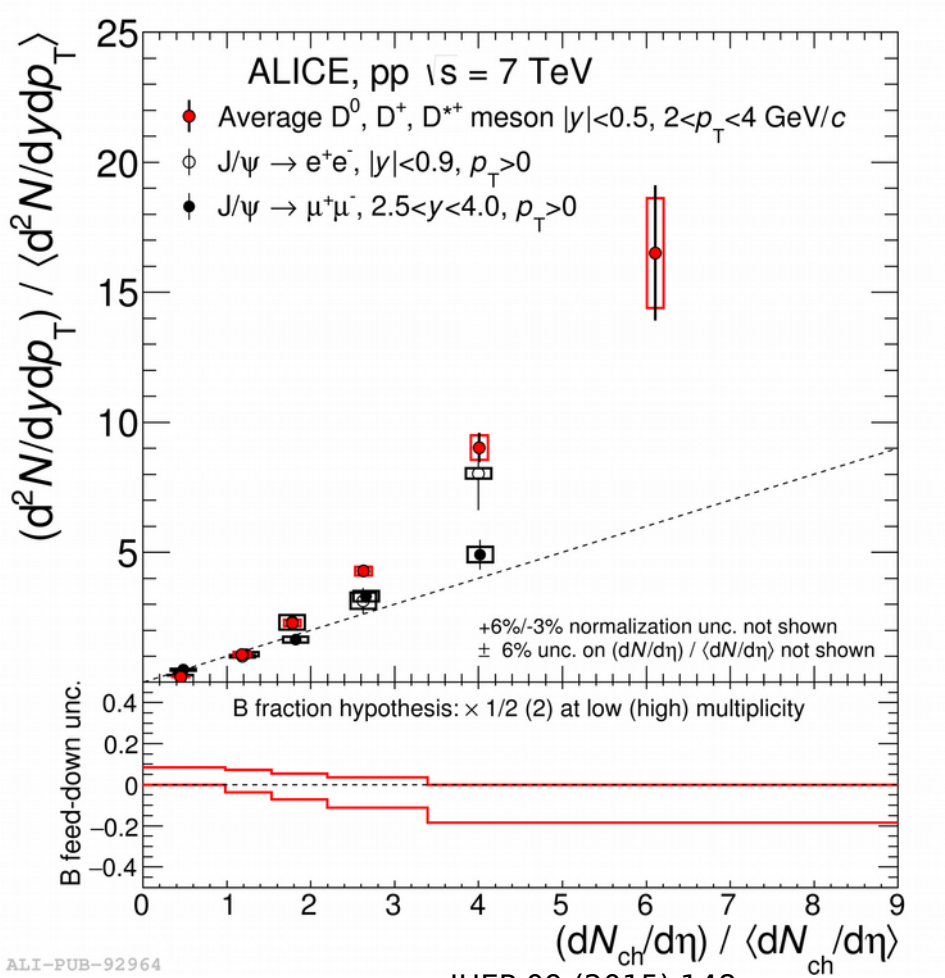


JHEP 09 (2015) 148

- Prompt J/ψ and D mesons at mid-rapidity

  → same trend for open and hidden charm

Heavy quark production as function of multiplicity

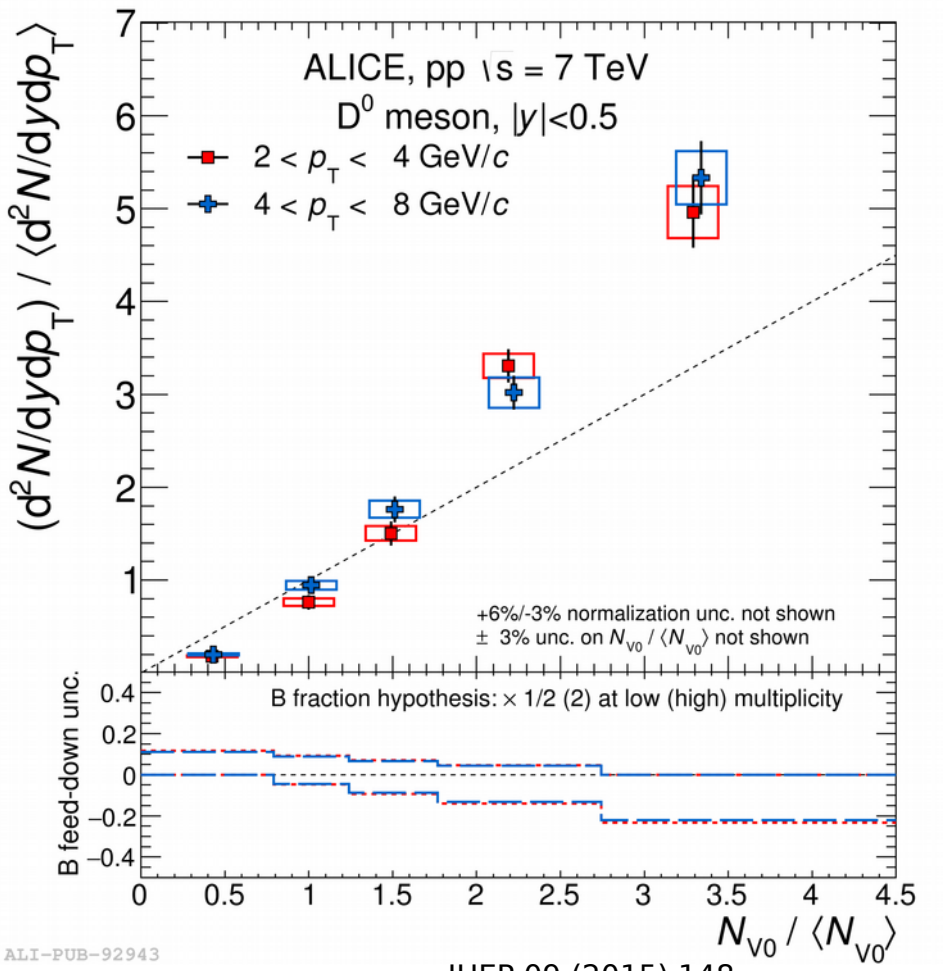


JHEP 09 (2015) 148

- Inclusive J/ψ at mid- and forward rapidity and D mesons at mid-rapidity

  → same trend for open and hidden charm

Heavy quark production as function of multiplicity

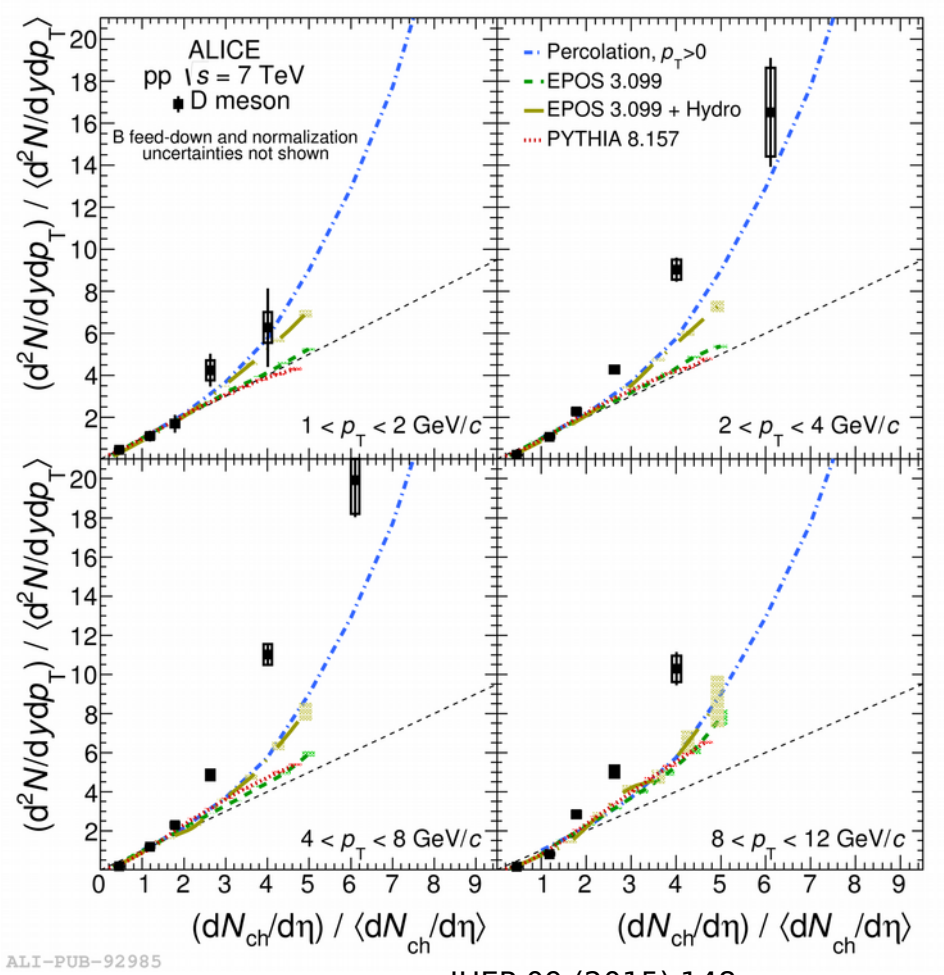


JHEP 09 (2015) 148

- D^0 mesons at mid-rapidity
- Different multiplicity estimator: energy deposited in V0 detector

  → introducing η gap between measuring multiplicity estimator and measured quantity
  → remove auto-correlation
- Same trend as for charged track multiplicity estimator

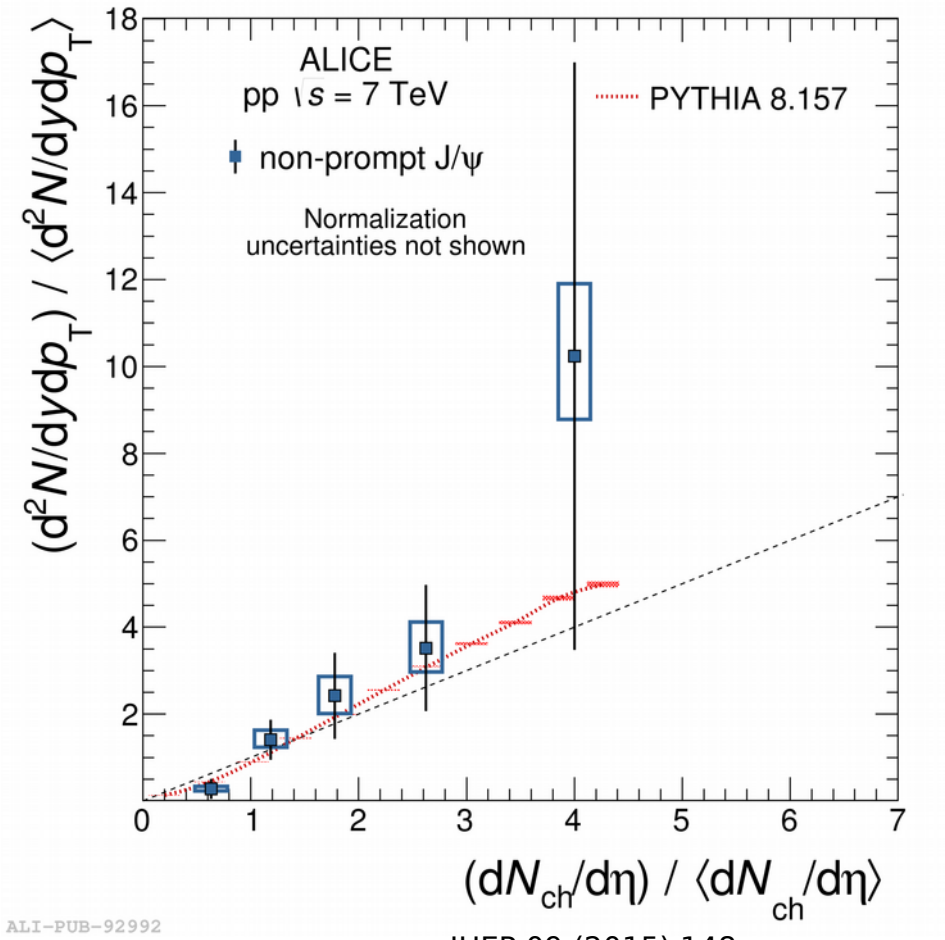
Heavy quark production as function of multiplicity



JHEP 09 (2015) 148

- D mesons at mid-rapidity
- PYTHIA 8 (new treatment of MPI) predicts linear increase with multiplicity
- EPOS with hydro expects stronger than linear increase

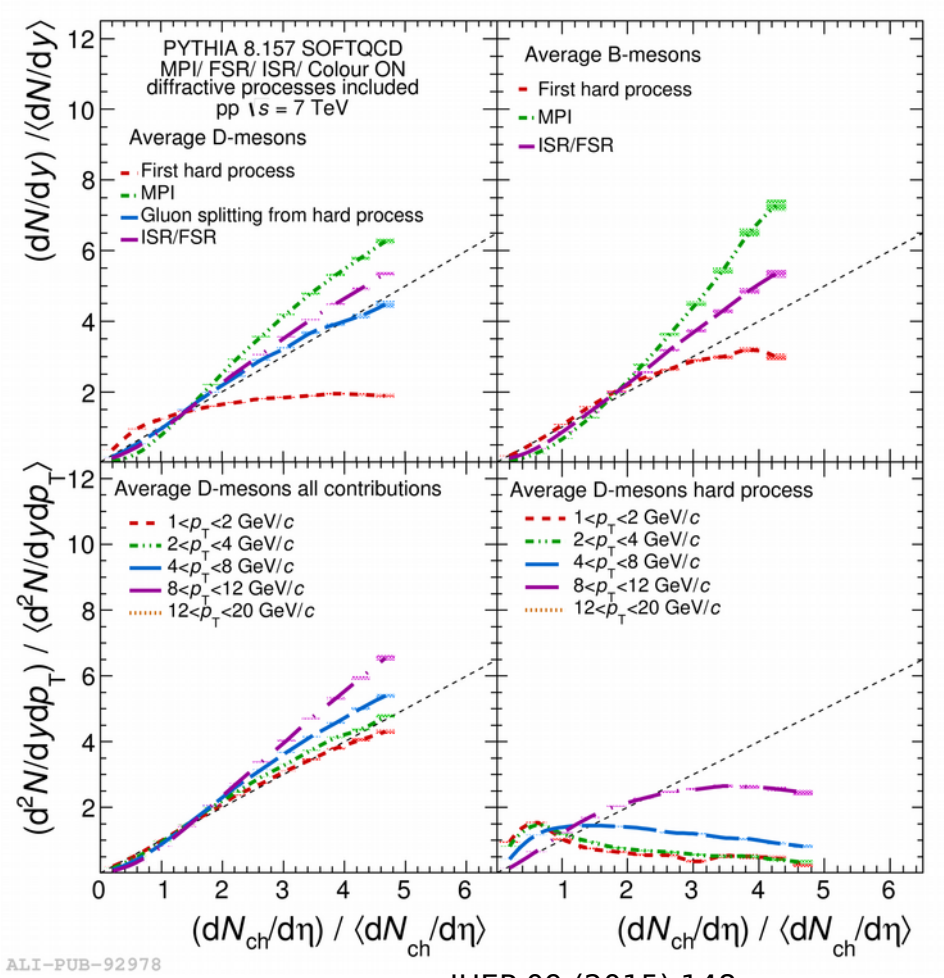
Heavy quark production as function of multiplicity



JHEP 09 (2015) 148

- J/ψ from B meson decay
- PYTHIA 8 (new treatment of MPI) predicts linear increase with multiplicity

Heavy quark production as function of multiplicity



JHEP 09 (2015) 148

- D and B mesons
- PYTHIA8: first hard scattering processes flatten with higher multiplicity
- stronger increase for MPI

Heavy quark production as function of multiplicity

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Origin of c and b quark content		D mesons	B mesons
First hard process		11%	36%
	gluon fusion	2%	15%
	c/b sea	9%	21%
Hard process in MPI		21%	24%
Gluon splitting from hard process		6%	included in ISR/FSR
ISR/FSR		62%	40%
Remnant		$< 0.2\%$	$< 0.4\%$

Table 2: Contribution of the different production processes to the total D- and B-meson production in PYTHIA 8.157 [31] for pp collisions at $\sqrt{s} = 7$ TeV.

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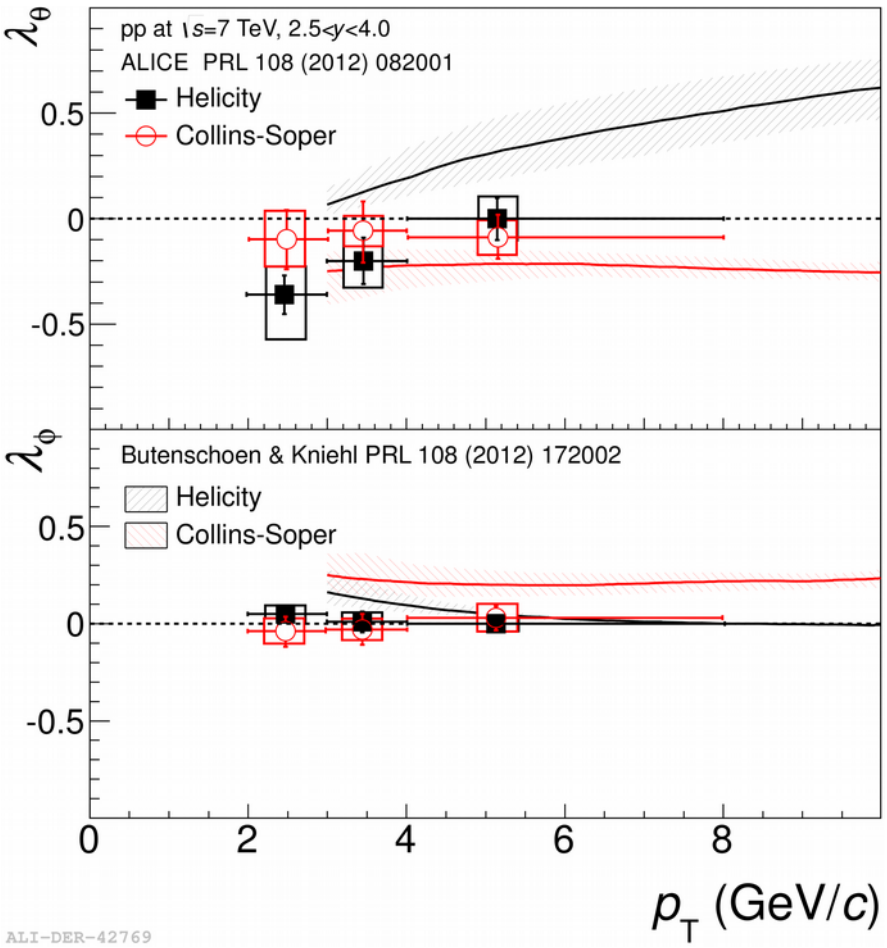
Polarization



- J/ψ polarization at forward rapidity compatible with 0
- Important test for charmonium production models